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# Facilitating breakdown in noble gasses at near-atmospheric pressure by using antennas

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**Abstract.** Electrical breakdown in near-atmospheric pressure noble gasses requires voltages that are quite high, which is undesirable for a large number of possible applications. Metallic structures (antennas) were used on the outer side of the lamp burner to enhance the electric field locally while keeping the same potential difference across the electrodes. Optical and electrical measurements were performed in an argon or xenon atmosphere at 0.3 or 0.7 bar, with 4 or 7 mm between the electrode tips. We used rod-shaped tungsten electrodes of 0.6 mm in diameter. We found that both active and passive antennas facilitate breakdown, and we demonstrated the differences between the two types and their effects on the breakdown process.

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## 1. Introduction

Electrical breakdown in gasses is an extensively researched topic, as it holds interest for academia and the industry alike. The lighting industry has been working on understanding the breakdown processes for decades, the research covering orders of magnitude in pressure for different gasses, voltage forms and various external influences, like UV irradiation. The breakdown process needs to be well understood because it is an essential part of lamp ignition. However, certain properties of the breakdown process, like high speed of development and large jitter associated with breakdown, make the research difficult. The respective relative influences of these properties grow with the pressure of the gas studied. This is why the breakdown process in lamps, especially mid- and high-pressure lamps, is still under investigation [1–11].

The voltage needed for lamp ignition is in general higher than the voltage needed for steady-state operation. This is true for high intensity discharge (HID) lamps, and it remains a constant challenge because the lowering of the starting voltage of HID

lamps could open the door to more efficient or simply cheaper lighting. It has already been reported that the breakdown voltage can be lowered in several ways from the level needed by pulse-ignited lamps - by the use of AC voltage instead of pulses [6, 9, 10] or by using ignition helpers, such as UV irradiation or radioactive electron sources [12, 13]. The two latter forms of ignition aid reduce the statistical lag caused by the lack of free electrons in the gas gap. The reduction of the statistical lag ensures better ignition reproducibility and therefore better chances that the lamp will start during the ignition sequence at a given applied voltage.

The reduction of the breakdown voltage for lamps, not taking into account the reduction of the overvoltage caused by statistical lag, is in its essence a search for the way to either allow the breakdown process to happen in the reduced electric field lower than the minimum value needed now, or to find a way to increase the reduced electric field in the lamp, while keeping the potential on the electrodes constant.

One of the ways to induce breakdown at lower reduced electric field than needed in a pure noble gas is to add a small admixture of a heavier noble gas to the lamp, for example to add a small amount of Xe in a lamp that operates with Ar as a starting gas [4]. At the same reduced electric field, electrons attain a higher mean energy in Ar than in Xe because of the lower electron-atom collision frequency [14]. However, Xe has a lower ionization potential than Ar. What we get as a result is the higher mean electron energy in Ar atmosphere, but we ionize Xe, which has a lower ionization potential. This effectively lowers the reduced electric field needed for the discharge to develop. The same would work for other noble gas combinations, for example small admixtures of Ar in He or Ne. In addition, in noble gas mixtures such as Ar-Ne, the Penning effect has a strong influence on the breakdown voltage as well. This feature is often used to lower the breakdown voltage in HID lamps.

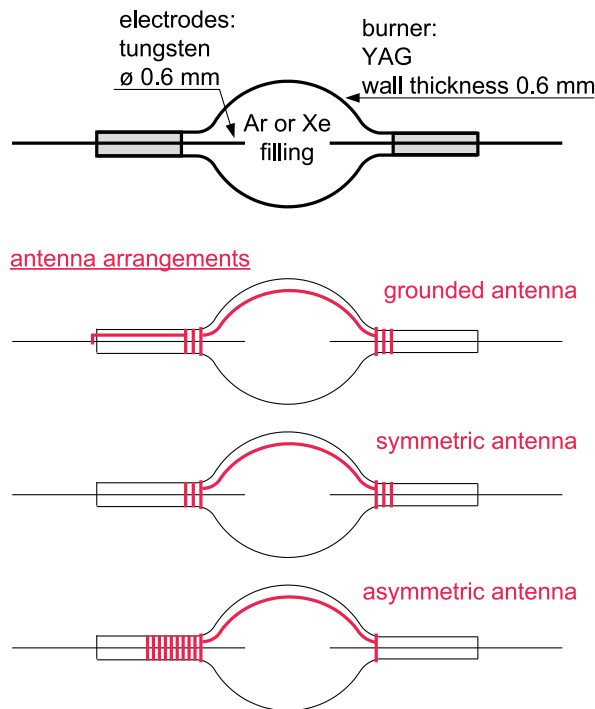
A way of increasing the reduced electric field in the lamp while keeping the potential of the electrodes at the same level and not changing the pressure of the gas is using electrodes with sharp features. However, as soon as a lamp starts burning, sharp features tend to become smoother as a consequence of high electrode temperature. Therefore, sharper electrodes usually do not allow for better ignition properties.

An alternative way of achieving a higher electric field in the plasma region is to use metallic structures on the outer side of the lamp burner. These structures are called "antennas". The role of an antenna is to bring a finite potential to the vicinity of the electrode system, or later, to the growing discharge. A finite potential close to the electrodes, if chosen properly, could enhance the electric field in the lamp burner by a significant amount with respect to the electric field originally imposed by the electrodes only. In this way, a lower voltage could be used while still maintaining the electric field level needed for breakdown. One of the first commercial lamp in which antennas were used was the high-pressure sodium lamp [15], but the underlying physics that influences the breakdown process was not described.

Controlling the discharge with the aid of a metal structure that doesn't take direct part in the discharge formation is not an idea that has been widely researched or

documented. The aim of this paper was to study the breakdown process under the influence of antennas, to show how it compares with the breakdown process in the lamp without antennas [9] and to explain the observed effects. We have performed optical and electrical measurements to characterize the AC breakdown process of near-atmospheric pressure noble gas discharges for three different antenna arrangements. We show the differences between the active and passive arrangements and how they influence the breakdown process.

## 2. Experimental setup

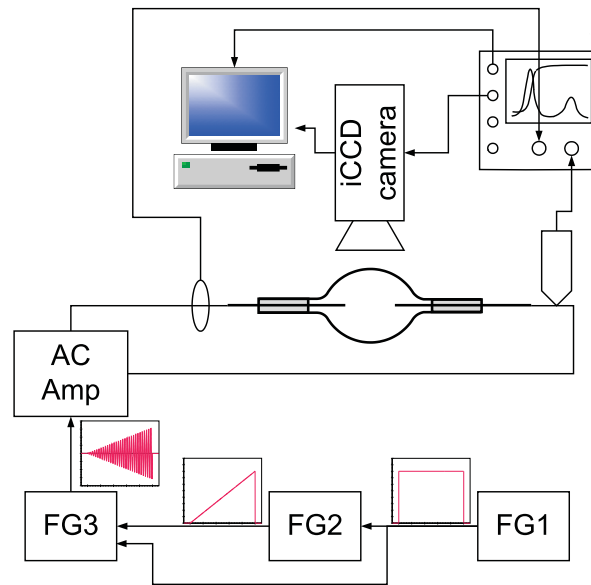


**Figure 1.** Schematic representation of the lamp burner and antenna arrangements. The top arrangement shows the active (grounded) antenna, connected to the grounded electrode on the left-hand side. The other two antennas are passive (floating).

The experiments were done on the setup described in [9]. Instead of a vacuum chamber to study discharges, we used HID lamp burners filled with noble gas at near-atmospheric pressure. The geometry was that of a 70W Philips HID burner commonly used in metal-halide lamps, schematically shown in figure 1. The burners were made of YAG (Yttrium Aluminium Garnet), which is a transparent material and therefore allows imaging of the breakdown process. It was also chosen for the similarity of its dielectric properties ( $\epsilon_r = 11.7$ ) to that of PCA (Polycrystalline Alumina) with  $\epsilon_r = 9$ , which is a material normally used in HID lamp burners. The electrodes we used were 0.6 mm in diameter, rod-shaped and made of tungsten. The distance between the electrode tips was set to 4 or 7 mm. The burners were filled with 0.3 or 0.7 bar of noble gas.

**Table 1.** Lamp types we used in the experiments.

Gas	Pressure Pressure [bar]	Electrode distance [mm]	Number of available lamps
Ar	0.3	4	6
		7	5
	0.7	4	3
		7	5
Xe	0.3	4	3
		7	2



**Figure 2.** Schematics of the setup used in the experiments.

The schematic representation of the setup is shown in figure 2. The AC voltage was produced by three function generators and subsequently amplified by a combination of a high-frequency amplifier (AR Worldwide 800A3) and a home made transformer coil. The three function generators were coupled together in the following manner: the first function generator (FG1) provided a pulse that triggered both the second and the third function generator (FG2 and FG3) and determined the duration of the final AC signal. The second function generator provided a linear positive ramp, which we used as modulation for FG3. FG3 produced an AC signal with linearly rising amplitude, which is what we used for our experiments.

When establishing the minimum breakdown voltage for lamps with specific antenna arrangement, the slope of the voltage amplitude was varied between 20 and 1280 V/ms. The frequency was varied between 500 kHz and 1 MHz.

For optical imaging we used an AC signal of constant amplitude and frequency, but at an overvoltage - a voltage higher than the minimum breakdown voltage. The reason for this is that the statistical time lag associated with breakdown processes decreases as the overvoltage increases [16, 17]. Statistical lag is a source of large jitter during the AC breakdown process [9, 11]. This jitter would have made the imaging of the breakdown process very difficult if not impossible in a reasonable time frame. Although it was possible to minimize the statistical lag in another way, for example to use UV irradiation [12, 16, 18], we chose not to proceed in this direction, because we were not able to establish with certainty that UV irradiation would only reduce statistical lag of the breakdown process.

For optical measurements we used a Princeton Instruments UNIGEN II filmless GEN III iCCD camera with a  $1024 \times 1024$  pixel array. We took photographs of the visible part of the breakdown process, with gate widths ranging from 100 ns to 1 to 5 voltage cycles (1 cycle =  $1.25 \mu\text{s}$ ). There were no multiple photographs of the same discharge taken, due to limitations of our equipment. Every photograph we present in this paper was taken during a separate breakdown process.

The electrical measurements were done by the means of a high voltage probe and an oscilloscope.

### *2.1. Antenna arrangements*

We explored three different antenna arrangements, shown in figure 1. Antennas are metallic structures placed on the outer side of the lamp burner wall. For their construction we used metal wire of 0.25 mm diameter, which we wound tightly around the burner to avoid as much as possible the capacitances not accounted for in the calculations. The first antenna arrangement had three windings at each side of the burner wall, connected to each other by a single straight wire. This type of antenna arrangement is also referred to as the *antenna strip*. The antenna was connected to the grounded electrode, making its potential constant at all times. The second arrangement was a symmetrical passive antenna which differs from the first arrangement only in that it wasn't connected to an electrode, but was instead at floating potential. The third arrangement was an asymmetrical passive antenna, with 10 windings at the grounded side of the lamp and just one at the active side. Its potential was also floating, but it behaved in a different way than that of the symmetrical antenna. For more explanation, see the Discussion section.

An active antenna arrangement is more difficult to use in practice, because of the difficulties in the production process. Connecting the antenna to one of the lead wires is a complex step in the manufacturing procedure, and it has a low success rate.

We had several lamps of the same type made (we define *lamp type* as a specific combination of gas, pressure and distance between the electrode tips), in order to avoid any error that might be caused by bad electrodes, impurities or gas leakage. The lamps we used are given in table 1. When performing breakdown voltage measurements,

we took 10 measurements for each lamp and for each data point. We calculated the averages and the standard deviation for each lamp, and then calculated the same for each lamp type. The values and the corresponding standard deviations shown in the graphs represent the average and the deviation for the corresponding lamp type. The optical measurements were done only for argon filled lamps with electrode gap of 7 mm, and for only one lamp of each type.

### **3. Results**

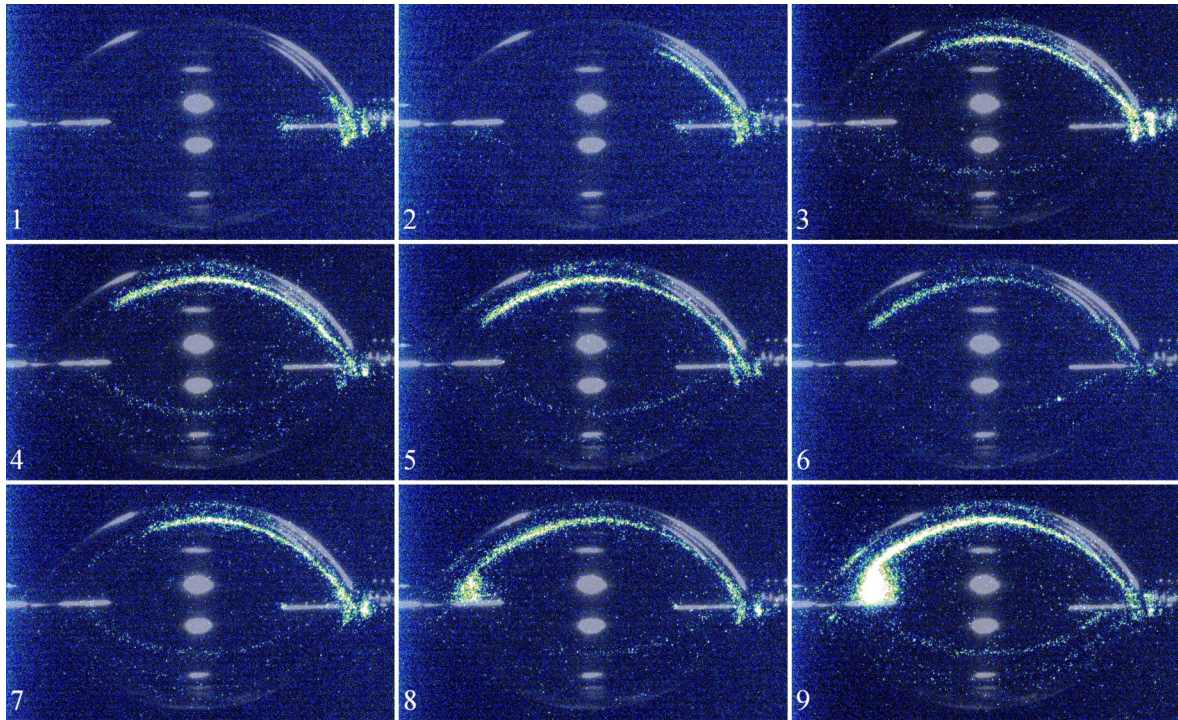
The *breakdown process* consists of several stages - the inception of the discharge, followed by the growth of the discharge, which leads to formation of a charged channel that bridges the gas gap and ends in the *breakdown moment*. The *breakdown moment* is the moment when the conductance of the channel that previously formed in the gas gap rapidly increases, causing conduction current to start flowing through the channel and a drop of potential difference across the gap. *Breakdown voltage* is the minimum voltage applied across the electrodes at which breakdown is achieved.

The term *overvoltage* is used in this paper quite a few times. In general, this is a voltage that is higher than the minimum voltage needed for breakdown. We could not measure the true minimum breakdown voltage, instead we used as a reference the voltage needed for breakdown at a given frequency and the voltage amplitude slope of 100 V/ms. Overvoltage in this paper is always determined as the excess voltage amplitude when compared to the breakdown voltage at 100 V/ms amplitude slope; it is always given as percentage. Overvoltage was employed only for imaging purposes, to reduce the statistical lag which would have otherwise made our optical measurements impossible in a reasonable time frame.

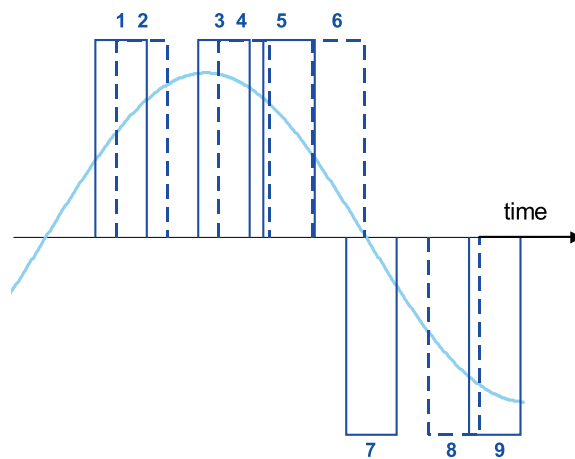
#### *3.1. Influence of antennas on discharge development*

We observed the formation of a charged channel in 0.3 and 0.7 bar argon atmosphere for the three antenna types described in the previous section. Figure 3 shows the formation of the charged channel in the 0.3 bar argon, at 7 mm electrode gap and with an active (grounded) antenna. The photographs were taken for an arrangement where the antenna strip was positioned on top of the lamp burner, like we have schematically shown in figure 1. The grounded electrode of the lamp is shown on the left side of every photograph, and the active electrode (the one on 800 kHz sine potential) is on the right. It is shown in the figure 3 that a charged channel formed on the inner side of the burner wall, directly below the antenna. In the environment with no external electric field modifiers (antennas), the same discharge (0.3 bar argon in 7 mm gas gap) at the same frequency formed a charged channel in the gas volume [9].

The photographs presented in figure 3 were taken for an overvoltage of 39%. The visible part of the breakdown process under these circumstances took between 1 and 1.5 voltage cycles. The lowering of the overvoltage to 30% did not increase the duration



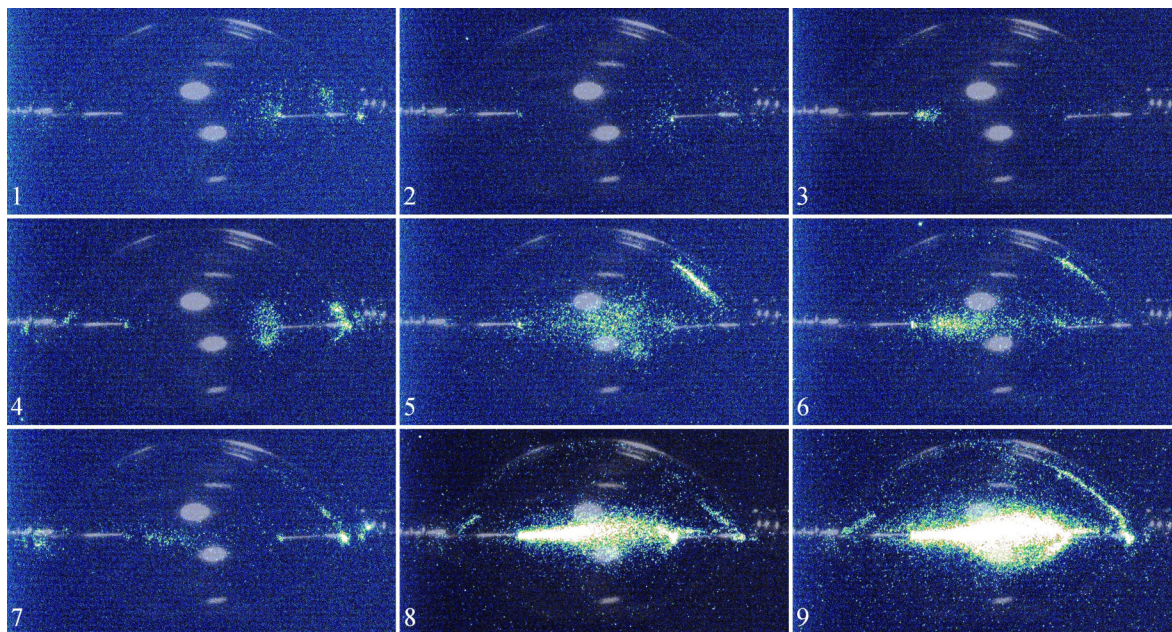
**Figure 3.** The visible part of the breakdown process aided by an active grounded antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 4 for the timing of each frame.



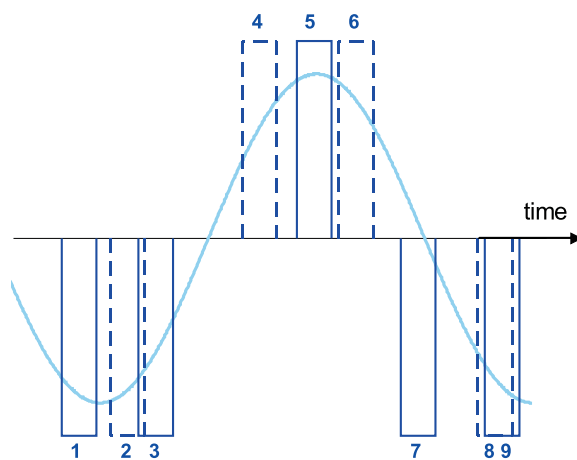
**Figure 4.** Schematic representation of the timing of the breakdown process aided by grounded antenna shown in figure 3. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.

of the breakdown process. In comparison, the duration of the breakdown process in the same conditions, but without the antenna present, took about 15 voltage cycles, as





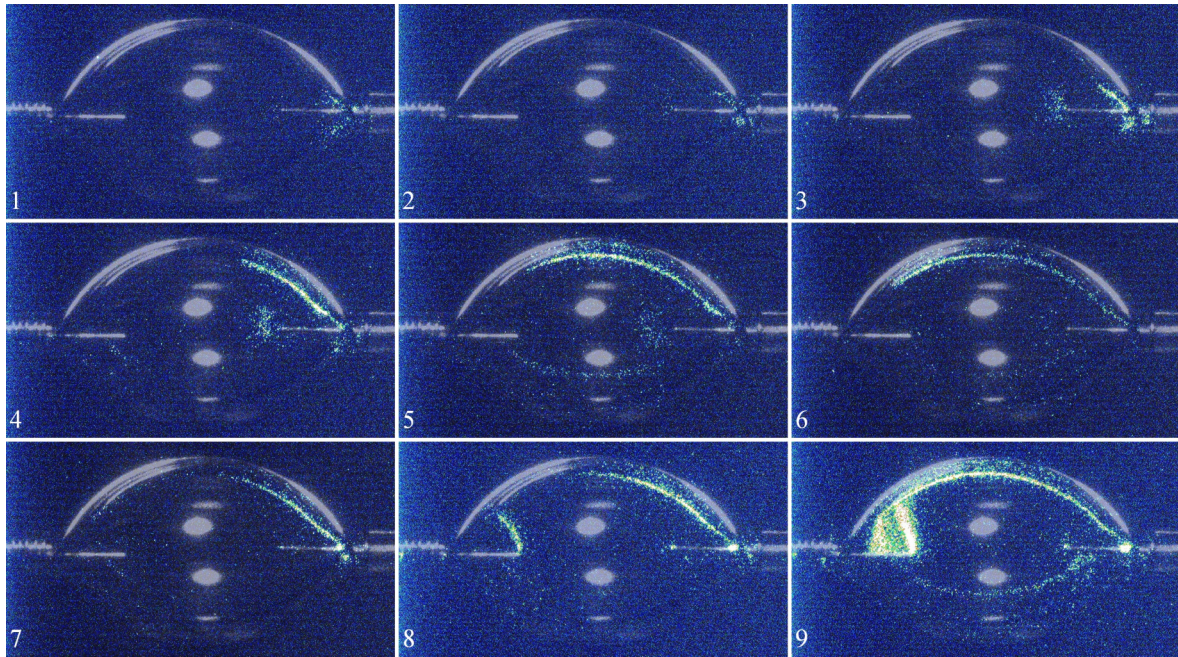
**Figure 5.** The visible part of the breakdown process aided by a symmetric passive antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 6 for the timing of each frame.



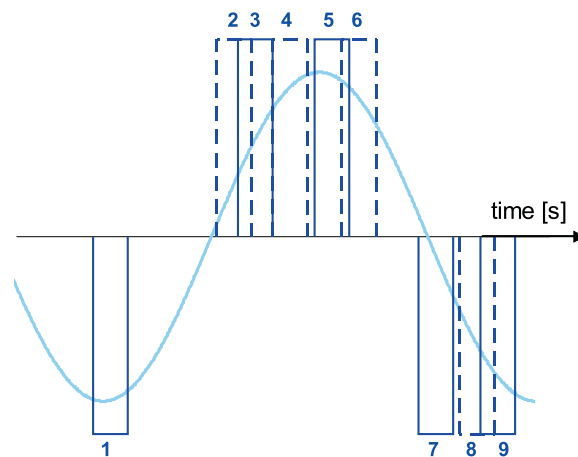
**Figure 6.** Schematic representation of the timing of the breakdown process aided by a symmetrical passive antenna shown in figure 5. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.

shown in [9].

We can see that the discharge started as a cloud-like formation around the active electrode, not at its tip, but directly below the place where the antenna structure forms three windings around the side of the lamp burner. With the ground potential so close



**Figure 7.** The visible part of the breakdown process aided by an asymmetric passive antenna in 0.3 bar argon at 7 mm gas gap. The camera gate was 100 ns. See figure 8 for the timing of each frame.



**Figure 8.** Schematic representation of the timing of the breakdown process aided by an asymmetrical passive antenna shown in figure 7. Each 100-ns frame is represented as a part of the sine that stands for the potential on the charged electrode. The frames with even numbers are drawn using dashed lines to improve clarity.

to the active electrode, this became the place of the maximum electric field instead of the electrode tip. The discharge then proceeded to form a thin channel that grew along the burner surface; the channel was completed after connecting to the grounded electrode. The same behaviour was observed regardless to the voltage amplitude we

employed.

Figures 5 and 6 show the breakdown process in 0.3 bar Ar when a passive (floating) symmetric antenna is used on the outer side of the burner wall. There are two important points that distinguish this breakdown process from the one previously shown - first, the breakdown process takes longer when the passive antenna is used, between 2 and 3.5 voltage cycles depending on the voltage amplitude (for 37% and 14% overvoltage, respectively). As a general rule, with the increase of voltage amplitude the formative time becomes shorter. At 0.7 bar, the discharge takes from 1.5 voltage cycles for 121% overvoltage to 12 voltage cycles for 31% overvoltage to form.

The second difference between the discharges at 0.3 and 0.7 bar helped by passive symmetric antennas is that at 0.3 bar, there are two competing discharges that form in the lamp - one along the burner surface below the antenna, and the other in the gas between the electrode tips. When the overvoltage is decreased, the wall discharge disappears and only the one in the gas is formed. This does not hold for the 0.7 bar argon discharges - as far as we have observed, these always form on the burner surface.

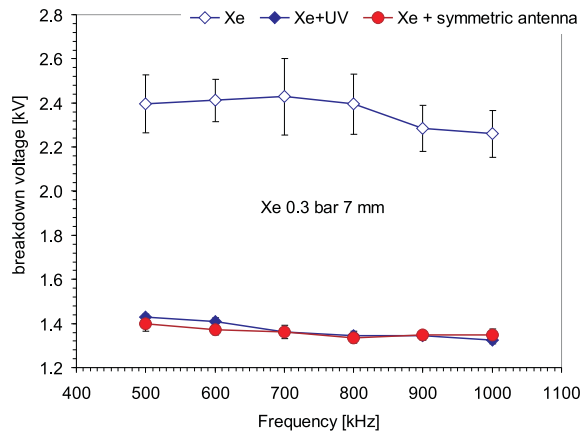
Figure 7 shows the breakdown process when an asymmetrical antenna is employed. As already described in the previous section, the asymmetrical antenna features 10 windings at the grounded side of the lamp (shown on the left side of each photograph) and just one at the active side (the right side of each frame). By using this arrangement, we have tried to come close to the results achieved in the case of an active antenna. For explanation, see the Discussion section.

The asymmetrical arrangement shortened the breakdown process to a value between 2 to 4.5 voltage cycles for the overvoltages between 34% and 9% in 0.3 bar argon. Also, as can be seen in the figures, the discharge looks much more like a discharge formed under the influence of an active antenna - there are no competing discharges, just one single channel growing on the inner surface of the burner wall.

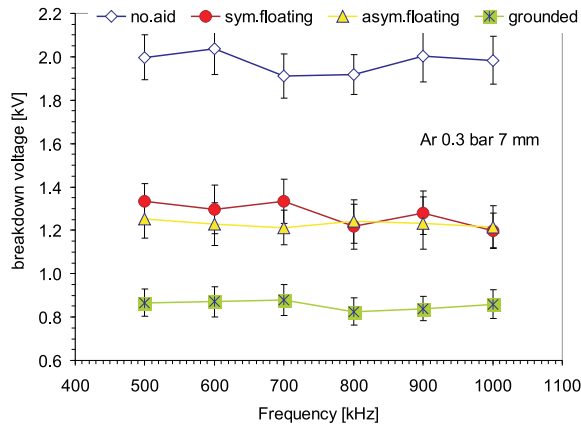
### *3.2. Effect on breakdown voltage*

Except having an effect on the duration of the breakdown process and the way the charged channel forms in the gas, different antennas also have an influence on the breakdown voltage. We measured the breakdown voltage by applying sine voltage with linearly rising amplitude across the electrodes, changed the slope of the voltage amplitude and the frequency and observed the effects.

Figure 9 shows the breakdown voltage for xenon at 0.3 bar and 7 mm electrode gap at a voltage amplitude slope of 100 V/ms, as a function of voltage frequency. A passive symmetrical antenna arrangement was used to aid the breakdown process. The results are compared to the data collected for a non-aided and a UV-aided breakdown process. As we have argued in [9], the UV irradiation employed in experiments that did not feature antennas had one main effect: to reduce the statistical time lag of the breakdown process to a very low value. We can see in the figure that for the case of Xe at 0.3 bar, the symmetrical antenna lowers the breakdown voltage to the level of



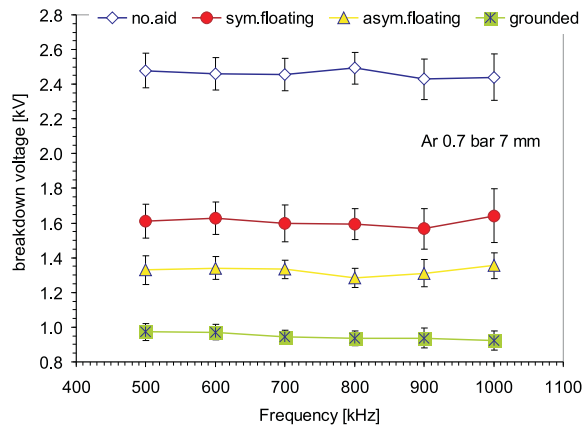
**Figure 9.** Breakdown voltage of the 0.3 bar xenon discharge with 7 mm between the electrode tips. We compare the breakdown process aided by the symmetrical passive antenna with the UV-aided and non-aided case.



**Figure 10.** Breakdown voltage as a function of frequency for 0.3 bar argon discharge and 7 mm gas gap. We compare the results obtained for symmetrical and asymmetrical antennas with the data for the active grounded antenna and the non-aided case.

the UV-aided process. This is not the case for all lamp types. The breakdown voltage of a 0.3 bar Xe discharge with 4 mm gap and a symmetric passive antenna is  $26 \pm 10\%$  higher than the breakdown voltage of a UV-aided breakdown process, at 800 kHz. For discharges in argon the breakdown voltage is  $11 \pm 5\%$ ,  $14 \pm 6\%$ ,  $13 \pm 6\%$  and  $6 \pm 5\%$  higher when a symmetrical antenna is used than for UV-aided breakdown. The given values correspond to argon at 0.3 bar and a 4 mm gap, 0.3 bar and 7 mm gap, 0.7 bar and 4 mm gap and 0.7 bar and 7 mm gap at 800 kHz, respectively.

Figures 10 and 11 show the relative influence of different types of antennas, compared to the non-aided case. The measurements were done for the voltage slope at 100 V/ms and at frequencies ranging from 500 kHz to 1 MHz. In both pressures the antennas significantly lowered the breakdown voltage with respect to the non-aided



**Figure 11.** Breakdown voltage as a function of frequency for 0.7 bar argon discharge and 7 mm gas gap. We compare the results obtained for symmetrical and asymmetrical antennas with the data for the active grounded antenna and the non-aided case.

case. In addition, the lamps with active (grounded) antennas required less voltage for a successful breakdown process. The results show that the lamps with symmetrical and asymmetrical passive (floating) antennas required a slightly higher voltage for breakdown than the lamps with the active antennas. Also, in the case of 0.7 bar, the lamps with asymmetrical antennas have a lower breakdown voltage than with the symmetrical arrangement.

#### 4. Discussion

In this paper we characterized the AC breakdown process in argon and xenon in the presence of electric field enhancers (antennas). We experimented in the frequency range between 500 kHz and 1 MHz, using three different antenna types: an antenna on the constant potential (active antenna), and two floating (passive) antennas, one symmetrical and the other asymmetrical. We have shown the effect of the antennas on the breakdown voltage and on the formation of the discharge. The measurements show that, compared to the non-aided breakdown processes, the discharges aided by antennas form on the dielectric surface, rather than in the gas volume. They also have a shorter formation time, and the breakdown process is possible at lower voltages.

The idea behind the usage of antennas was to examine the effects of modifying the electric field in our experimental arrangement. We wanted to examine in which way would the breakdown process be influenced in these changed conditions and to explain in which way exactly do the active and the passive antennas work. To this end, first we did some static electric field modelling, using the commercially available software package by *Integrated Engineering Software* to simulate static electric fields in lamps. We used *Electro* for 2D and *Coulomb* for 3D simulations. It is important to note that a static electric field model can account for the electric field in a lamp system only in

**Table 2.** Increase of electric field in various antenna arrangements, with respect to the reference cases without antennas, in two- and three-dimensional models.

		2D simulation		3D simulation	
		anode tip	anode base	anode tip	anode base
Floating antennas	spiral	18%	100%	18%	90%
	uniform coating	24%	117%	-	-
	strip	-	-	32%	89%
Active antennas	grounded spiral	127%	282%	110%	253%
	grounded strip	-	-	86%	258%

the inception phase of the discharge initiation, before the discharge starts propagating in the gas between the electrodes.

The results are summarized in table 2. The simulations predict that the initial electric field in the lamp was enhanced by 32% at the electrode tips and 89% at the base of the electrodes when a symmetrical passive antenna was used. An active grounded antenna enhanced the initial electric field by 86% and 258% at the charged electrode tip and base, respectively. The electric field at the base was around 32% of the strength of the field at the electrode tip in a reference, non-aided case without an antenna present. Thus, the breakdown process could start at voltages lower than needed for the case without electric field enhancers, because for the same potential difference across the gas gap, we achieved higher electric field at the places in the lamp that are strategically important for discharge initiation.

It is not enough just to ease the inception of the discharge; the electric field strength has to be higher than a certain threshold value in order to maintain its growth. This is why, as a general rule, an arrangement that would just enhance the electric field near the electrodes would not be efficient in lowering the minimum voltage needed for the breakdown process. Instead, we used antennas that stretched across the whole length of the lamp burner. In this way, the proximity of a finite potential to the discharge growing on the inner side of the lamp burner enhanced the electric field at the tip of the growing discharge above the value that could have been achieved without an antenna structure. The overall effect was that a discharge was able to initiate and grow at a voltage lower than the voltage needed without the usage of antennas.

#### 4.1. Effect of the dielectric surface

When assessing the influence of antennas on the breakdown process in our experimental geometry, we cannot limit ourselves to the amplification of the reduced electric field in the lamps. The antennas moved the inception spot of the discharge from the electrode tips [9] to the electrode base, allowing the discharge to grow on the dielectric surface instead of in the gas volume. This was true for all the observed breakdown processes,

with exception of 0.3 bar argon with a symmetric passive antenna, where the electric field at the tip was still strong enough to make the electrode tip a strong contender for the inception place of the discharge.

The advantage of a discharge growing on the dielectric surface is that surface discharges in argon grow at higher speed than in the gas volume even without the help of an antenna, as we have previously shown in [19]. The higher speed of growth suggested not only an electric field amplification by the dielectric surface, but also that the surface was acting as a pre-charged source. It has already been shown that the preexisting charge on the dielectric surface eases discharge growth [20].

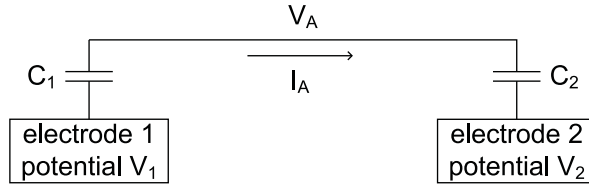
Still, the surface discharges in the experiments on which we report here were of a different type from the ones discussed in [19]. The antenna-aided surface discharges can be thought of as *guided discharges* [20, 21]. In guided discharges the presence of the grounded electrode on the far side of the dielectric causes a high electric field amplification. It has recently been conclusively shown [22] that the gas processes are boosted in such a degree that they dominate the surface growth of the discharge. The high electric field amplification can be thought of as an additional effect that allows the discharges to form in shorter times and at lower voltages compared to the non-guided surface discharges.

Taking other effects into account, it has been shown that a discharge forming in the vicinity of the test system can also act as an ignition aid, not by supplying the charged particles, but through light emission [17, 23–26]. In particular, it has been shown [27] that surface discharges are efficient sources of UV irradiation and can be used in complex systems like lasers to ensure high enough density of free electrons in the gas gap. Following this argument one can imagine how two competing discharges, like we have seen in our experiment in the case of 0.3 bar argon, can influence each other’s development.

It can be said that the antennas we used not only acted as electric field amplification devices, they also allowed the discharge to grow on the dielectric surface of the burner, additionally easing breakdown. The downside of the discharges’ growing on the burner surface when the breakdown process was aided by antennas, is that the gap the discharge had to cross was longer than that of a discharge growing in the gas between the electrode tips. This could cause a competition between the surface and volume discharges, as was observed in the case of 0.3 bar argon discharges aided by symmetrical passive antennas.

#### *4.2. Active and passive antennas*

There is one significant difference between active and passive antennas. The potential of an active antenna is set by physically connecting the antenna to another conductor at a certain potential. This implies that it is possible to fix the potential of an active antenna irrespective of the system we are experimenting on. In our experiments, we connected the active antenna to the grounded electrode, making sure that its potential stays constant. In this way we ensured the proximity of the ground potential to the



**Figure 12.** Schematic representation of the electrical circuit using passive antennas.

active electrode and later to the growing discharge, making certain that the electric field at the electrode and at the discharge tip would be significantly amplified with respect to the conditions in a non-aided breakdown process.

The potential of passive antennas is floating, and induced by the electric field set by the electrodes. Our passive antennas featured windings on both sides of the lamp and a piece of wire across the lamp burner, connecting the windings on the sides of the lamp. The schematic representation of the circuit can be seen in figure 12.  $V_1$  and  $V_2$  represent the potentials at the electrodes, and  $I_A$  and  $V_A$  the current flowing through the antenna and the antenna potential, respectively. The antenna is connected to the potential of the electrodes through capacitances  $C_1$  and  $C_2$ .

The current flowing through a passive antenna can be calculated using Ohm's law

$$(V_1 - V_2) = I_A \left( \frac{1}{i\omega C_1} + \frac{1}{i\omega C_2} \right) \quad (1)$$

Potential of an antenna can also be expressed in the following ways, according to the circuit shown in the figure 12

$$V_A = V_1 - \frac{I_A}{i\omega C_1} \quad (2)$$

$$V_2 = V_A - \frac{I_A}{i\omega C_2} \quad (3)$$

Combining these equations, we arrive at the expression for the potential of the floating antenna

$$V_A = V_1 \frac{C_1}{C_1 + C_2} + V_2 \frac{C_2}{C_1 + C_2} \quad (4)$$

When we want to apply the formulation shown above to our own experiment, we choose electrode 2 to be the grounded one, thus setting  $V_2 = 0$ . This gives the final expression for the potential of the passive antenna in our experiment

$$V_A = V_1 \frac{1}{1 + C_2/C_1} \quad (5)$$

In the case of a symmetric antenna, the capacitances that couple the antenna potential to that of the electrodes in the lamp are equal ( $C_1 = C_2$ ), and the potential of the antenna is equal to one half of the potential of the charged electrode, with respect to ground potential. This is only half of what we achieve with the use of an active grounded antenna. Therefore, the electric field amplification is lower in the case of the



symmetric passive antenna, and we need a higher voltage on the active electrode to enable the breakdown process.

One can design a passive antenna with properties such that the antenna potential would be closer to the potential of one electrode than of the other, by adjusting the ratio of capacitances  $C_1$  and  $C_2$ . In our case, we have made an asymmetrical passive antenna with 10 windings at the grounded side of the lamp, and just one on the side of the active electrode, making  $C_2 = 10C_1$ . According to equation 5, the potential of such an antenna is

$$V_{asymmetric} = 0.09V_1 \quad (6)$$

Effectively, the asymmetric passive antenna we used should have ensured similar conditions during the breakdown process as the active grounded antenna. From the measurements of the breakdown voltage shown in figures 10 and 11, it is clear that this is not true during the whole breakdown process. This is discussed in the next section.

#### *4.3. Passive antennas during the breakdown process*

The considerations described above are valid for conditions in the lamp before the discharge inception, when the potential distribution in the lamp is given only by the electrode and dielectric geometry and the potential of the electrodes. As soon as the discharge is initiated and a glowing region forms at the base of one of the electrodes, as is indeed the case (see figures 5 and 7), the ratio of capacitances  $C_1$  and  $C_2$  changes. This is an essential difference between active and passive antennas - the potential of an active antenna is not affected by the discharge growing close to the dielectric surface.

Let us consider the capacitances  $C_1$  and  $C_2$  in passive antennas. As we have already stated, the antennas were secured at both ends of the lamp by a number of windings. We can approximate the capacitance between an electrode of radius  $a$  and an antenna ring on the outer surface of the lamp burner of radius  $c$  by an expression for a section of a coaxial cable. We have to take into account two capacitances in series - one between the electrode and the inner surface of the lamp burner of inner radius  $b$  ( $C_{gas}$ ) and one caused by the lamp burner itself ( $C_{YAG}$ ).

$$\frac{1}{C_{ring}} = \frac{1}{C_{gas}} + \frac{1}{C_{YAG}} \quad (7)$$

$$C_{gas} = 2\pi \frac{\epsilon_0 l}{\ln(b/a)} \quad (8)$$

$$C_{YAG} = 2\pi \frac{\epsilon_0 \epsilon_{YAG} l}{\ln(c/b)} \quad (9)$$

$l$  is the thickness of the wire we used for the construction of the antennas and  $\epsilon_{YAG}$  is the relative dielectric constant of the dielectric lamp material. The resulting capacitance for one antenna winding is

$$C_{ring} = 2\pi \frac{\epsilon_0 l}{\ln(b/a) + \frac{1}{\epsilon_{YAG}} \ln(c/b)} \quad (10)$$

The capacitance of  $n$  rings is

$$C_n = nC_{ring} \quad (11)$$

As soon as a diffuse discharge fills the volume between the electrode and the lamp burner wall at the neck of the burner, the part of the capacitance in equation 10 accounting for the effect of the space between the electrode surface and the burner surface can be left out. The following expression for the capacitance for one antenna winding can be used when a diffuse discharge forms around the electrode

$$C_{ring} = 2\pi \frac{\epsilon_0 \epsilon_{YAG} l}{\ln(c/b)} \quad (12)$$

As shown in the Results section, the breakdown process in argon features a discharge growing on the inner surface of the lamp burner just below the antenna, for both pressures when the asymmetrical passive antenna was used and for 0.7 bar with the symmetrical antenna arrangement. This calls for another correction to the capacitance ratio between the two sides of the lamp.

The capacitance between the thin charged channel growing on the inside surface of the lamp burner and the antenna can be approximated by the parallel plate model

$$C_{strip} = \epsilon_0 \epsilon_{YAG} \frac{dl}{c-b} \quad (13)$$

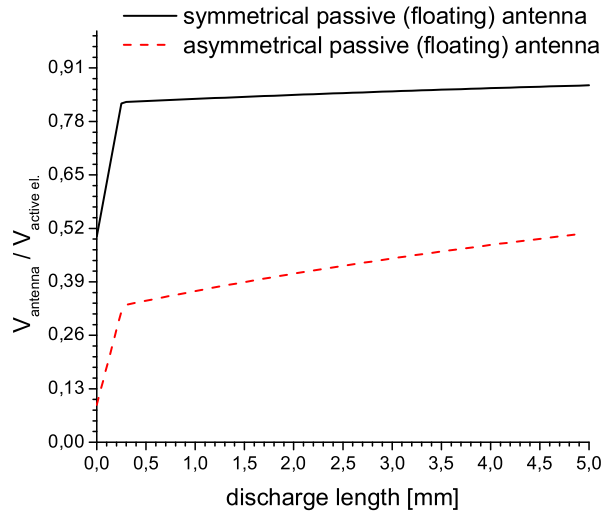
$d$  is the length of the charged channel that formed below the antenna,  $l$  is the thickness of the antenna wire, and  $c-b$  is the thickness of the dielectric YAG lamp burner. In our calculations we have not taken into account the potential drop across the charged channel that forms during the breakdown process - we have assumed that the potential is the same as at the active electrode. We can make this assumption because the channel that forms is indeed ionized, but the validity of this premise does not hold for long channels.

The values we used for calculations are listed below. They correspond to real dimensions of the electrodes and the YAG burner used in the experiments.

$$\begin{aligned} a &= 0.3 \text{ mm} \\ b &= 0.4 \text{ mm} \\ c &= 1 \text{ mm} \\ l &= 0.25 \text{ mm} \\ \epsilon_{YAG} &= 11.7 \end{aligned}$$

The capacitance in the case of one antenna winding at the base of the electrode was  $C_{ring} = 3.8 \times 10^{-2}$  pF.

Everything we described above taken into account, we can follow the potential of a passive antenna as the discharge initiates and grows towards the grounded side of the lamp. Results of this consideration are shown in figure 13. The graph shows the ratio of the potential of the antenna and the active electrode as a function of the length of



**Figure 13.** Influence of the discharge length along the inner burner wall on the ratio of the potential of the passive antennas to that of the charged electrode.

the discharge. As our intention was to use the antennas as electric field enhancers, the desired values of  $V_A/V_1$  in our experiment would be as small as possible, so that the potential difference between the discharge and the adjacent antenna would be large. It is apparent that the potential of a passive antenna changes drastically over the course of the breakdown process, due to the growth of the discharge.

The initial values for  $V_A/V_1$  correspond to the ratios obtained for the time before any discharge growth, given in equation 5. The step increase to less favourable values is caused by the appearance of the diffuse discharge at the base of the charged electrode, that fills the volume between the electrode surface and the burner wall. One can notice a further increase of the ratio  $V_A/V_1$ , caused by the growth of a thin channel that originates at the base of the charged electrode.

Figure 13 shows why the asymmetric passive antennas in our experiments did not perform nearly as well as the active grounded antennas, regarding the enhancement of the electric field in the lamp during both initiation and growth of the discharge. It also shows that the passive antennas do not provide a very large amplification of the electric field. Even though the starting conditions appear promising, the emergence of the discharge in the lamp causes the potential of the antenna to be closer to the potential of the active electrode, lowering the effect of the electric field amplification.

Figure 13 shows the evolution of the antenna potential for a simple case when the discharge is initiated only at the charged electrode. The reality is a bit more complicated, because it sometimes involves partial discharges on the grounded side of the lamp as well. A diffuse discharge at the base of the grounded electrode, of the same size as the one on the opposite side of the lamp would bring the ratio  $V_A/V_1$  close to its initial value, thus creating once again a more favourable environment for the growth of the discharge. This more favourable state would prompt an easier growth of the discharge coming from

the active side, but this growth would again increase the ratio  $V_A/V_1$ . Consequently, in reality we would expect an oscillatory behaviour of the  $V_A/V_1$  ratio, causing the speed of growth of the discharge to experience oscillations as well. However, the nature, timing and significance of these oscillations depend to a great extent on the size of the diffuse discharge that would presumably appear at the base of the grounded electrode and its timing, the values of  $C_1$  and  $C_2$  and the electrode gap. Therefore, there is a whole class of possible outcomes that can potentially result from calculations of the ratio  $V_A/V_1$ , and most of them have a reasonable chance of happening in real systems.

As a result of the analysis presented above, one can conclude that there are specific aspects of antenna design that have a great influence on antenna performance. We propose three important aspects in passive antenna design, when the desired use of the antenna is to amplify the electric field set by the electrode system:

- (i)  $C_2/C_1$  prior to discharge initiation should be as large as possible
- (ii)  $C_2/C_1$  during the discharge development should be as large as possible
- (iii)  $C_1$  should be as small as possible and  $C_2$  should be as large as possible

In addition, the calculations we made are very sensitive to changes in dimensions. For example, a thicker YAG burner would significantly alter the graph shown in figure 13. It is, thus, important to realize that the effectiveness of an antenna can be influenced by the geometry of the experimental system as well.

## **5. Conclusions**

We have demonstrated the effects of active and passive antennas on the breakdown process in near-atmospheric pressure argon and xenon. We have shown that the amplification effect of the antennas on the reduced electric field has a twofold role - to increase the reduced electric field at the tip of the discharge, and to make it possible for the discharge to grow along the dielectric surface close to the electrode system. Both results have the same consequence; they ease the discharge initiation and growth and lower the minimum voltage required for breakdown. We have shown the difference between active and passive antennas. Active antennas were found to perform better than the passive ones in both configurations, and we have shown the importance of well-chosen parameters in the passive antenna design.

Having the basic understanding from the electrical point of view about the effects of the antennas on the discharge development, it is now possible to extend the research in various directions. As far as applications in lighting go, this opens a possibility to explore different antenna arrangements, more complex than the ones presented in this paper, and hopefully more efficient. In the field of guided surface discharges, there are lots of possibilities to further characterize the breakdown process. Experimental results that would ascribe relative importance to various processes present during the growth of guided surface discharges would be a great step in building a more comprehensive theory about surface discharges than what is available today.

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